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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

THIS ISSUE

VISCOSITY

Concluding the discussion of "Viscosity" which was begun in the May issue

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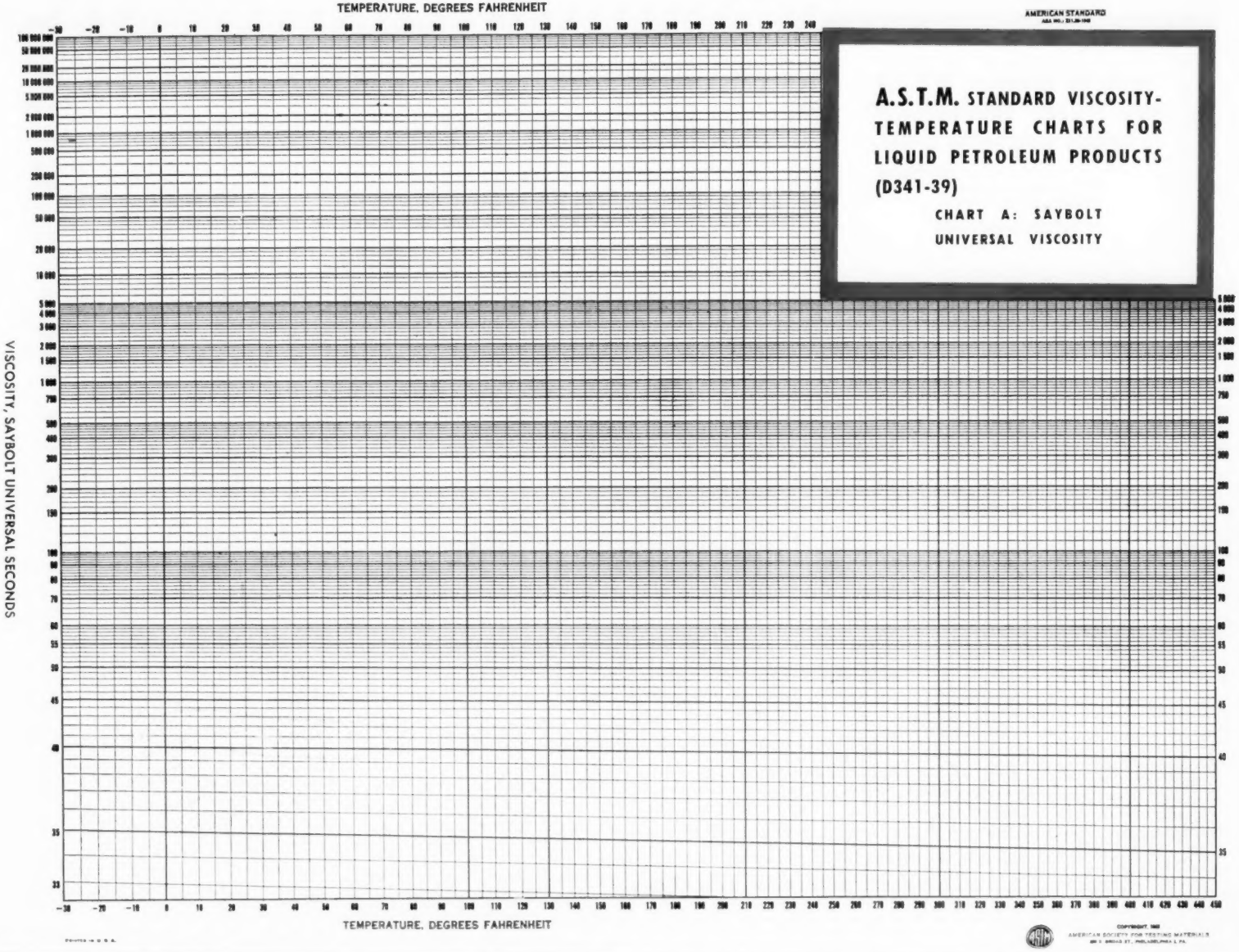
TEMPERATURE, DEGREES FAHRENHEIT
AMERICAN STANDARD
A.S.T.M. STANDARD VISCOSITY-TEMPERATURE CHARTS FOR LIQUID PETROLEUM PRODUCTS (D341-39)
CHART A: SAYBOLT UNIVERSAL VISCOSITY
VISCOSITY, SAYBOLT UNIVERSAL SECONDS
VISCOSITY, SAYBOLT UNIVERSAL SECONDS
TEMPERATURE, DEGREES FAHRENHEIT
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LUBRICATION

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VISCOSITY

PART III – TURBULENCE

THE PRECEDING discussion on the flow of viscous fluids was limited to streamline flow, in which the fluid flows as in a series of parallel or concentric surfaces having relative velocity, but no intermingling or mixing between one and another. This discussion will now be expanded to include turbulent flow which follows when fluid velocity is sufficiently increased. The classic demonstration of this phenomenon was given in 1883 by Osborn Reynolds when he admitted a fine thread of colored liquid into the center of a stream of water flowing into a glass tube with a submerged bell mouth. When water flowed at low velocity, streamline flow was indicated by a steady thread of color which remained surrounded by the stream for the whole length of the tube, as illustrated in Figure 18. As the velocity was continuously increased, turbulent flow started suddenly at a point about 30 or more diameters of the tube from the entrance, as indicated by the colored thread expanding into a band of color which filled the remainder of the tube. When viewed in a darkened room by a flashing or stroboscopic light, it was seen that the colored band consisted of distinct undulatory eddies as indicated in Figure 18A.

This region of turbulent flow is of great practical interest because the resistance to flow increases here more rapidly with velocity than in the streamline region,* and transfer of heat between the liquid and the metal is much more rapid. Furthermore, the flow of most fluids in pipes is in this region, in contrast to the flow in capillary tubes discussed previously, which is normally in the streamline region. The velocity which divides these two types of flow is called the *Critical Velocity*, and even under a definite set of conditions, it covers a considerable range of unstable flow and depends on whether the flow rate is increasing or decreasing, the roughness of the surface, etc. In general, however, this velocity increases with the viscosity and density of the fluid, and decreases with the diameter of the tube or pipe. The length has no effect on the critical velocity. This velocity may be determined from a ratio called the Reynolds Number. Expressed as a formula in any consistent system of dimensions:

$$\text{(Reynolds Number)} = \frac{\text{(velocity)} \times \text{(tube diameter)}}{\text{(kinematic viscosity)}} \quad \ldots (16)$$

The Reynolds Number at the critical velocity varies from about 2000 up to even 50,000 under exceptional conditions, but in general a value of

*In streamline flow: Resistance increases directly with velocity.
In turbulent flow: Resistance increases with (velocity) $^{1.7}$

THIS ARTICLE CONCLUDES THE DISCUSSION OF "VISCOSITY" WHICH WAS BEGUN IN THE MAY ISSUE.

Figure 18 — Streamline flow through a tube as indicated by a "thread" of dyed liquid entering the bell-mouthed end (at the left) with the fluid.

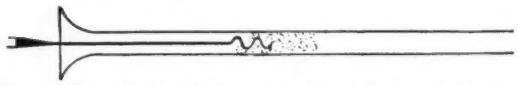


Figure 18A — The beginning of turbulent flow as indicated by the dyed thread of liquid as it breaks into eddies.

Figs. 18 and 18A
Courtesy of the McGraw-Hill Book Company, Inc., from "Fluidity and Plasticity" by Dr. Eugene C. Bingham

2320 is used, as the minimum value above which streamline flow becomes "metastable" and requires progressively smaller disturbances to cause its transformation into the turbulent region.

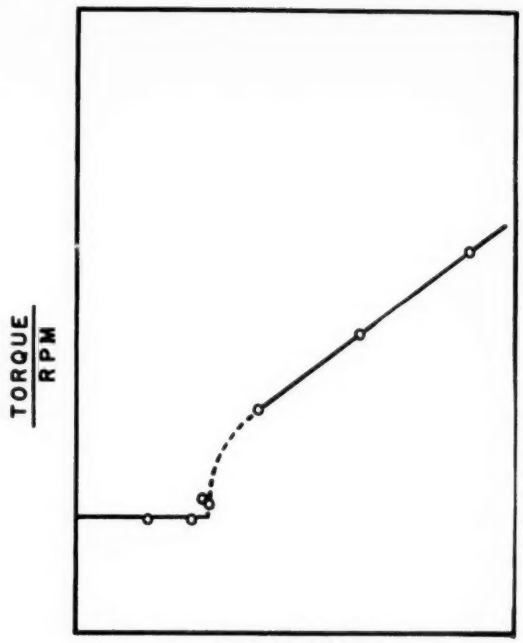
A more convenient equivalent form of equation 16 for commercial applications to flow in pipes in our usual system of measures is:

$$R = \frac{\text{(U. S. gallons flow per minute)} \times 100}{\text{(diameter in inches)} \times \text{(viscosity in cs)}} \quad \ldots (17)$$

The pressure required to overcome the fluid friction per 1000 feet of pipe may be determined from:

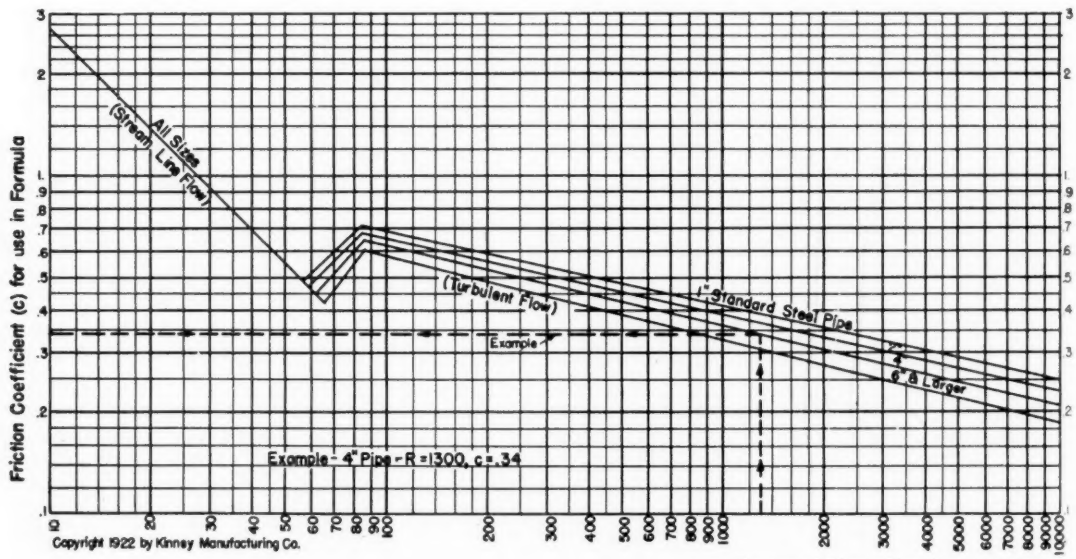
$$\text{(Pounds/sq. in)} = \frac{C\,\text{(gallons per minute)}^2 \times \text{(sp. gr.)}}{\text{(diameter in inches)}^5} \quad \ldots (18)$$

where C is taken from the chart of Figure 20 when the value R has been obtained from equation 17.



Courtesy of the McGraw-Hill Book Company, Inc., from "Fluidity and Plasticity" by Dr. Eugene C. Bingham

Figure 19 — The transition from streamline to turbulent flow as revealed by Torsion Type Viscometers. The horizontal line (at the left) indicates streamline flow; the dotted curved section, the unstable transition zone; and the straight inclined line indicates the stable region of turbulent flow.


Friction Coefficient (c) for use in Formula
All Sizes
(Stream) Line Flow
(Turbulent Flow)
1" Standard Steel Pipe
Example
4" & Larger
Example - 4" Pipe - R = 1300, c = .34
Copyright 1922 by Kinney Manufacturing Co.

Courtesy of Kinney Manufacturing Company

$$\text{Turbulence Factor (R)} \quad \text{—or—} \quad \frac{\text{Gallons per Minute} \times 100}{\text{Diam. in Inches} \times \text{Viscosity in cs.}}$$

Figure 20 — Chart for friction coefficients for liquid flow in commercial steel pipes.

The part of the chart to the left of a critical velocity factor R = 57 represents the streamline flow where the pressure increases directly with the velocity or flow rate.*

It is obvious that in small tube or capillary viscometers in which streamline flow is assumed, precautions should be taken to assure flow below the critical velocity. If this is not done, the indications of viscosity will be too high. An example of this is indicated for a torsion viscometer in Figure 19. Here the measure of friction drag has been divided by the velocity (or rpm). As long as the fluid flow is streamline, the indicated viscosity remains constant, as shown by the horizontal section of the line to the left. At the velocity of turbulent flow, the curve suddenly rises, and after passing through the uncertain transitionary zone indicated by the dotted line, settles down to a straight line with a constant slope.

*Pounds/sq. in. per 1000 feet $= \frac{0.275 \text{ (viscosity in cp)} \times \text{(gallons per minute)}}{\text{(diameter in inches)}^4}$

PART IV – EFFECTS OF TEMPERATURE AND PRESSURE

A. Temperature

The rate of change of the viscosity of a fluid with temperature, is not easily solved by formula and it has been found convenient to interpolate or extrapolate test data by means of charts. These temperature-viscosity relationships have such pronounced curvature that plots on rectangular coordinates are not satisfactory if they cover considerable range, because the viscosities at the high temperature side of the plot cannot be read with sufficient accuracy.

Several other ways of plotting these data have therefore been proposed. One of the first which naturally suggested itself was the use of logarithmic coordinates with the viscosity scale in centistokes. When the temperatures were expressed in Fahrenheit or Centigrade an improved chart resulted, as may be seen from Figure 21 which was published in the July 1920 Issue of LUBRICATION. Curves for various oils became straight enough in their center part for reasonable interpolation, though they were curved slightly at the ends, in opposite directions. The viscosity scale was sufficiently open to read with about equal accuracy at all points. The principal weaknesses of this chart were: First, the temptation to extrapolate the straight part of these curves (especially when data are not plotted above 210°F.), which has led to the astonishing conjecture that all oils have the same viscosity at some temperature where the extended straight parts of these graphs coincide. Second, the graphs cannot be used at 0 degrees or below. This latter fault was corrected by changing to a scale of absolute temperature instead of Fahrenheit, but the lines for various oils again became so decidedly curved that interpolation was uncertain.

The next step was an attempt to straighten these lines again by taking the log of the ordinate scale a second time, in other words, the log of the logarithm of the viscosity. The result was a series of lines for various oils which were surprisingly straight down to about 4 cs (40 sec Saybolt) and almost parallel for oils from similar crudes. Below 4 cs these lines began to curve downward. Furthermore, since there is no real logarithm of a negative number, it was not possible to obtain the log log of a number less than 1.0 cs. This chart was cut off at 40 seconds Saybolt and published in the June 1921 issue of LUBRICATION (see Figure 22, p. 65). Its decided usefulness immediately became evident. Many thousands of these charts were copyrighted and distributed by The Texas Company and used in industry. One of the significant indications of the value of this chart, which showed its need in industry, was the considerable number of similar charts which later were evolved both in this country and abroad. Possibly one reason for this competition was the unintended mystery surrounding this chart as a result of withholding the empiric formula on which it was based, pending an anticipated improvement to reduce the restrictions at low viscosities already mentioned.

In an attempt to extend the viscosity scale below 1 cs, a constant of 1.0 was added arbitrarily to the viscosity in cs before taking the log of its logarithm. This effected a marked reduction in the curvature of the graphs in their low viscosity regions, and even appeared to be a little too much correction, since the viscosity lines tended to become slightly concave upward where they had previously been curved downward. This led to trial of smaller constants than 1.0.

The results of varying this constant may be seen in Figure 23 in which high and low viscosity cuts from the same samples of crude oils are plotted from Lane and Dean's remarkably comprehensive data,[15]

[15] F. W. Lane and E. W. Dean – Ind. and Eng. Chem. *16*, p. 905, 1924. Viscosities were tabulated at 10°C. intervals on 12 or more fractions cut over the same temperature ranges, from 5 widely different crude oils.

with constants varying from 1.0 down to 0.4. On the high viscosity fraction (P-V-300), the negligible effect of varying this constant on the straightness of the lines and the slight effect on their slopes, is evident. On the low viscosity fraction (PA 150), the importance of the constant is obvious. As a result of this study, a constant of 0.7 was considered to give the best overall results, and was adopted for several charts, including one which was published in the 1927 International Critical Tables. This chart, together with all the points from Lane and Dean's data for fractions from the California crude, is shown in Figure 25 (p. 67).

Similar work sheets were made for the four other crude oil sources, and all demonstrated an equally remarkable family of straight and almost parallel lines down to at least 0.7 cs. A further study of these results is indicated in Figure 24 which shows the mean slope* for each cut from each crude[15] plotted against the viscosity of that cut at 212°F. Dot-and-dash lines connect cuts of all crudes which were made in the same temperature range. The uniform slope, and the resulting parallelism of the plots for the lubricating oil fractions from the Gulf Coast crude is noteworthy. So is the uniform increase of slope for the Pennsylvania crude cuts with decreasing viscosity, and the approach to each other of the slopes of cuts from all crudes at viscosities below about 1 cs. The effect of using a constant of 0.8 instead of 0.7 is indicated by the dotted curves for the Gulf Coast and Pennsylvania crudes.

As a result of this study, 0.7 was the value of the "viscosity constant" reported to the ASTM when the general form of the equation** was disclosed[16] to the committee assigned to standardize viscosity-temperature charts. A constant of 0.8 appeared preferable to the committee, and was adopted for the first ASTM charts.[17] By 1937 further study resulted in a revision of the ASTM charts to use a constant of 0.6 down to viscosities of 1.5 cs and an increased constant of 0.65 for the viscosity range from 1.5—1.0 cs; 0.70 for 1.0—0.7 cs and 0.75 for 0.7—0.4 cs.

A reduced copy of one of the present standard ASTM charts is shown as a frontis-piece in this issue. The slope of the low viscosity coordinate lines is due to the fact that they are drawn as equivalent Saybolt viscosities, which, as explained on page 58 (May issue), requires a temperature correction for conversion to kinematic viscosity, due to the cooling of oil as it flows from the Saybolt tube into its measuring flask. The chart, of course, is actually laid out on the basis of kinematic viscosity, even though only the equivalent Saybolt scale is indicated.

The original work on this chart which led to the plotting of straight lines by adding a constant to the viscosity before taking its log-log, is credited to MacCoull by the original ASTM Report.[17] The first log-log chart was published in LUBRICATION in 1921. Walther did some similar work in Germany (but without the added constant) in 1928[18] in which he referred to the use of a double logarithmic scale which he credited to Le Chatelier.[19]

In 1929 Walther wrote that he had been advised of The Texas Company's chart by Herschel of the U. S. Bureau of Standards[20] and implied that this chart had been worked out on a graphical basis. As a matter of fact, it was Herschel who had developed this graphical method.[21]

It was not until August, 1931 that Walther first published the constant in a log-log formula.[22] This is an interesting point since some physicists abroad

*The slopes indicated are those obtained mathematically, by dividing the differences between the log of the log of the viscosity (in cs) + 0.7, of any two points for a given oil fraction, by the differences in logs of the absolute temperatures (in degrees Rankin) at those two points.

**log log (sc+K) = —b log (temp. in ° Rankin) + a

16Letter of 19 May 1931

17API Proc. Div. of Refining, June 1932, p. 56.

18Erdöl und Teer 4, p. 510, 1928.

19Comptes Rendus des Seances de L'Academie des Sciences, Vol. 179 (1924) p. 518. M. LeChatelier proposed the simple log-log scale for use of molten glass only.

20Erdöl und Teer 5, p. 619, 1929.

21Oil and Gas Journal Dec. 2, 1926, pp. 146-182.

22Erdöl und Teer 7 382-4 25 Aug. 1931: p. 383 — footnote (9): "Für die Zurverfügungstellung von entsprechenden Diagrammen und Viskositätswerten ist der Verfasser Herrn Dr. Herschel vom Bureau of Standards, Washington, zu Dank verpflichtet."

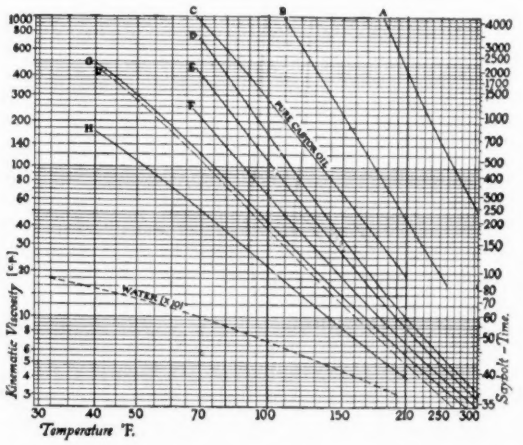
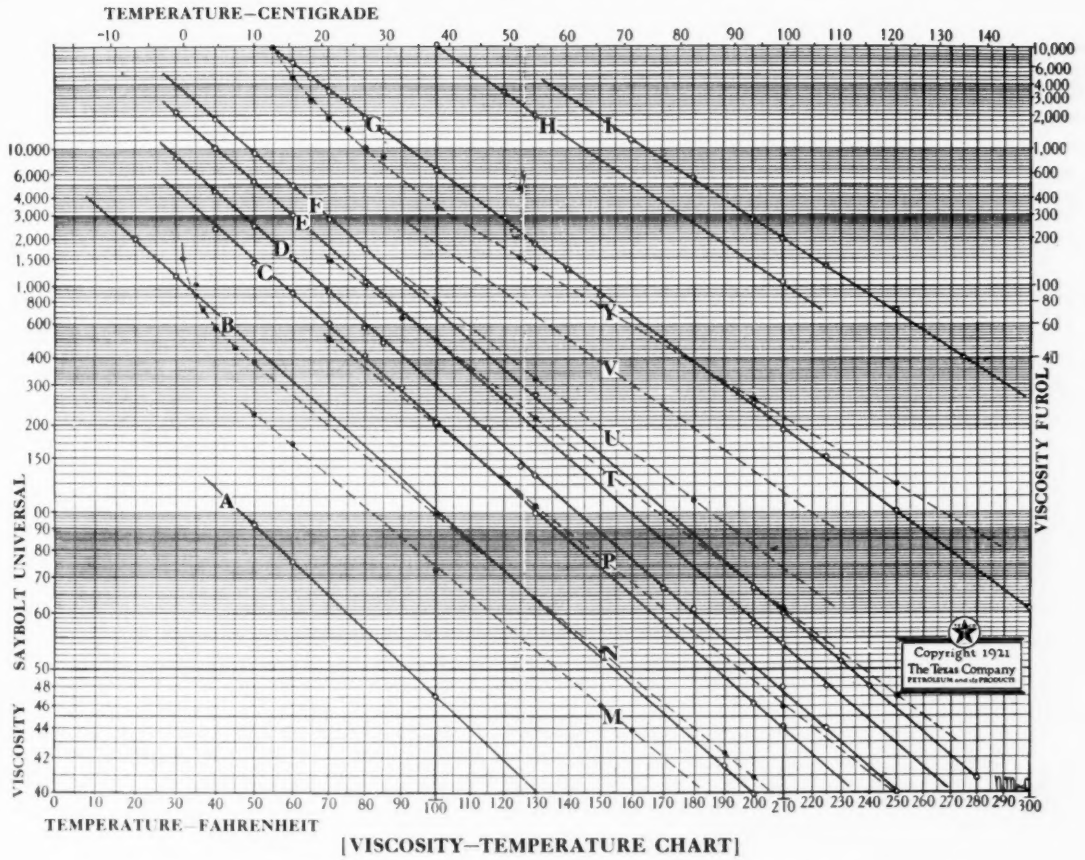


Figure 21 — Chart laid out on Log CS Versus Log F from "Lubrication", July, 1920.



[VISCOSITY—TEMPERATURE CHART]

Figure 22 — Chart laid out on Log-Log of CS Versus Log Abs. Temperature (°F.). From "Lubrication", June, 1921. Oils coded A to I are of Naphthenic type. Oils coded M to Y are Paraffinic. Note effect of wax crystallization at low-temperature end of oils N and Y.

have described the use of the log-log of viscosity plus 0.8 as "Walther's formula,"[23, 24] in technical publications, apparently being unaware of the prior use of this formula by The Texas Company.

B. Viscosity Blending Chart (Figure 26)

Early in the use of these charts, it was found that they were useful also, in approximating the viscosity of lubricating oil blends. The section between 0 and 100°F. was arbitrarily taken as a scale indicating the percentage of the *high* viscosity oil in a blend, the viscosity of which was marked at the suitable ordinate on the 100 line. The viscosity of the lower viscosity oil (at the same temperature) was indicated on the 0 line. A straight line plotted between these two points indicated the viscosities of mixtures of these two oils according to the scale which indicated the percentage of the high viscosity oil in the blend. This blending method was published at a later date[25] together with one of the first descriptions of The Texas Company's chart to be published outside of LUBRICATION. More recently charts have become available with a linear percentage scale, but they do not appear to be quite as accurate. It should be borne in mind that any chart is at best but a close approximation with the discrepancy increasing with the difference in viscosity of the two oils being blended.[26]

C. Effect of Temperature on Viscosity of Gases

Before leaving the effect of temperature on the viscosity of liquids, it will be of interest to note that temperature has an opposite effect on the vis-

[23] Inst. of Mechanical Engineers, Proc. 1937, p. 218-20.
[24] The Science of Petroleum, Vol. II (1938) p. 1087.

[25] Oil & Gas News, June 1924, p. 18, Dr. Roy Cross, "Viscosity Chart for Mineral Oils, and How to Use It."
[26] Technologic Papers — Bureau of Standards #164 (1920).

cosities of gases. While the viscosity of any liquid decreases with increasing temperatures, the viscosity of gases increases. Similar principles are used for the measurement of the viscosity of a gas as for a liquid, and some ingenious capillary tube instruments have been devised for this purpose in which the gas flow is accomplished by the fall of a small pellet of mercury in a connecting tube.[27] To give an idea of the relative magnitudes of the viscosities of gases, Table I has been prepared.

TABLE I
VISCOSITIES OF SEVERAL GASES AT 20°C. AND 1 ATM. PRESSURE

Gas	*Viscosity in cp*
Hydrogen	0.009
Helium	0.020
Carbon Dioxide	0.015
Air	0.018
Mercury Vapor at 273°F.	0.049

Because of the low values of gas viscosities, they are often expressed in terms of *micropoises*. Such units result in values 10,000 times as large as the centipoise values shown above.

While the viscosities of gases are obviously low, they may produce considerable drag on high speed machinery such as large electric generators, steam turbine rotors, centrifugal blowers, etc. Progress seems to be associated with continually increasing speeds of mechanisms, and viscous drag or "windage" of air may thus become increasingly important.

D. Effect of Pressure on Viscosity of Liquids

For some time it has been known that the viscosity of oil increases with pressure. This is, of course, a matter of importance in analyzing the hydraulics of oil performance in heavily loaded bearings. Because it is difficult to measure viscosities at very high pressures, the amount of such data is limited. Several research groups have been making studies of this subject, but for this article the general effect of pressure may be seen from Figure 27.[28] Mineral oils represented by the curves coded A to D, increased considerably in viscosity with pressure, and as a group, varied much more than the fatty oils, which fell in a separate group. As a contrast, water exhibited but little of this characteristic.

A comprehensive investigation of this subject has been under way since 1948 at Harvard University sponsored by a committee of the ASME. They have developed a viscometer which is fundamentally similar to that shown in Figure 6. Instead of a ball,

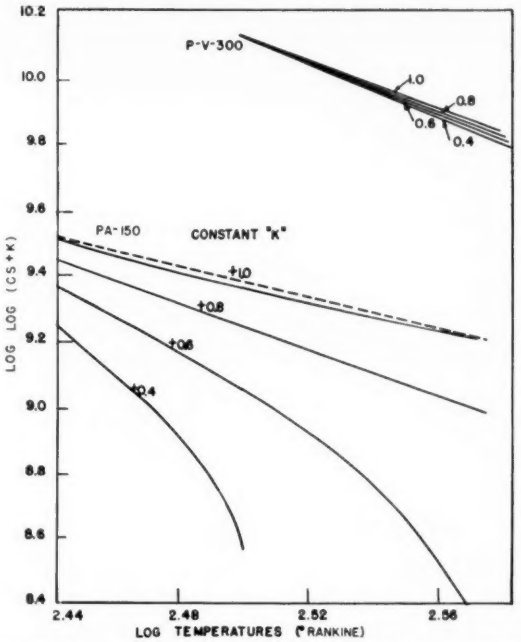


Figure 23 — Effect of various constants on the curvature and slope of viscosity-temperature curves.

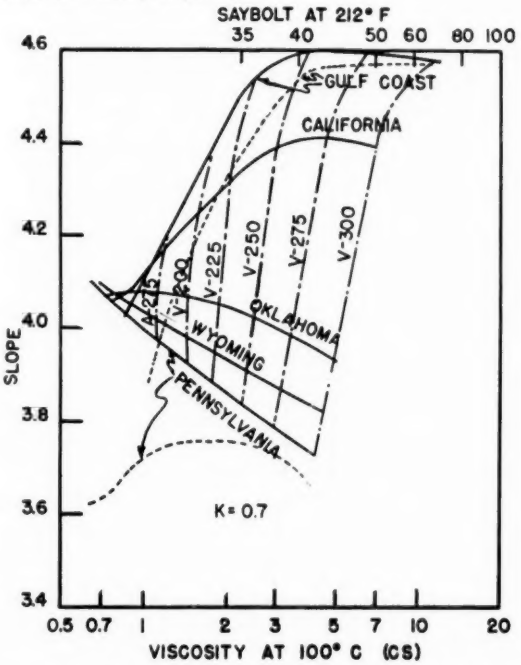


Figure 24 — Slope of various cuts from different crudes as affected by their viscosity. (Lane & Dean's Data.)

[27]The Viscosity of Gases at High Pressures. U. of Ill. Bul. Ser. No. 354 (1944) p. 19.

[28]Reproduced from "Lubrication" April 1921, p. 11.

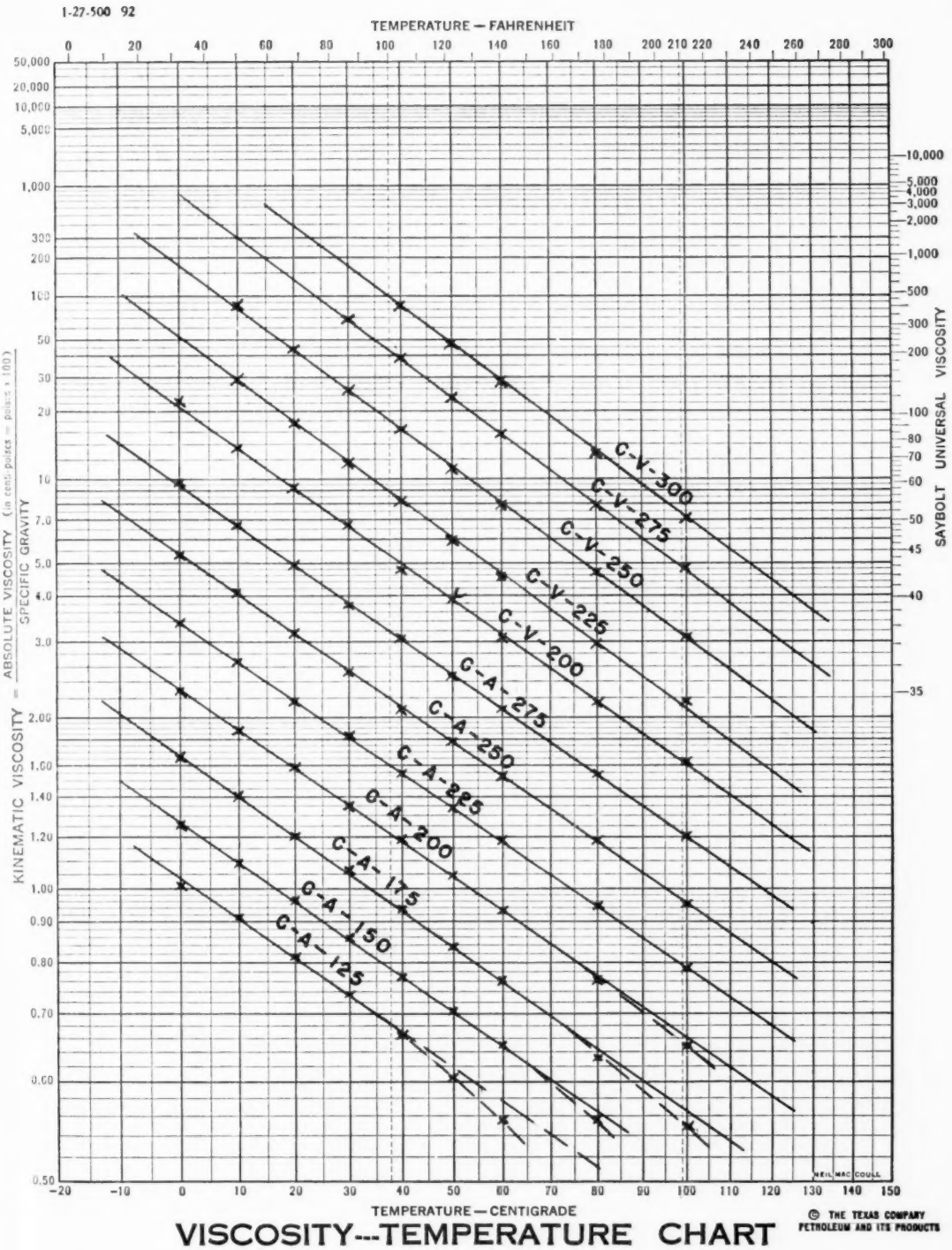


Figure 25 — Proof of the straight-line characteristic of the log-log chart (with an 0.7 constant) from 12 cuts of a California crude. (Lane & Dean's Data.)

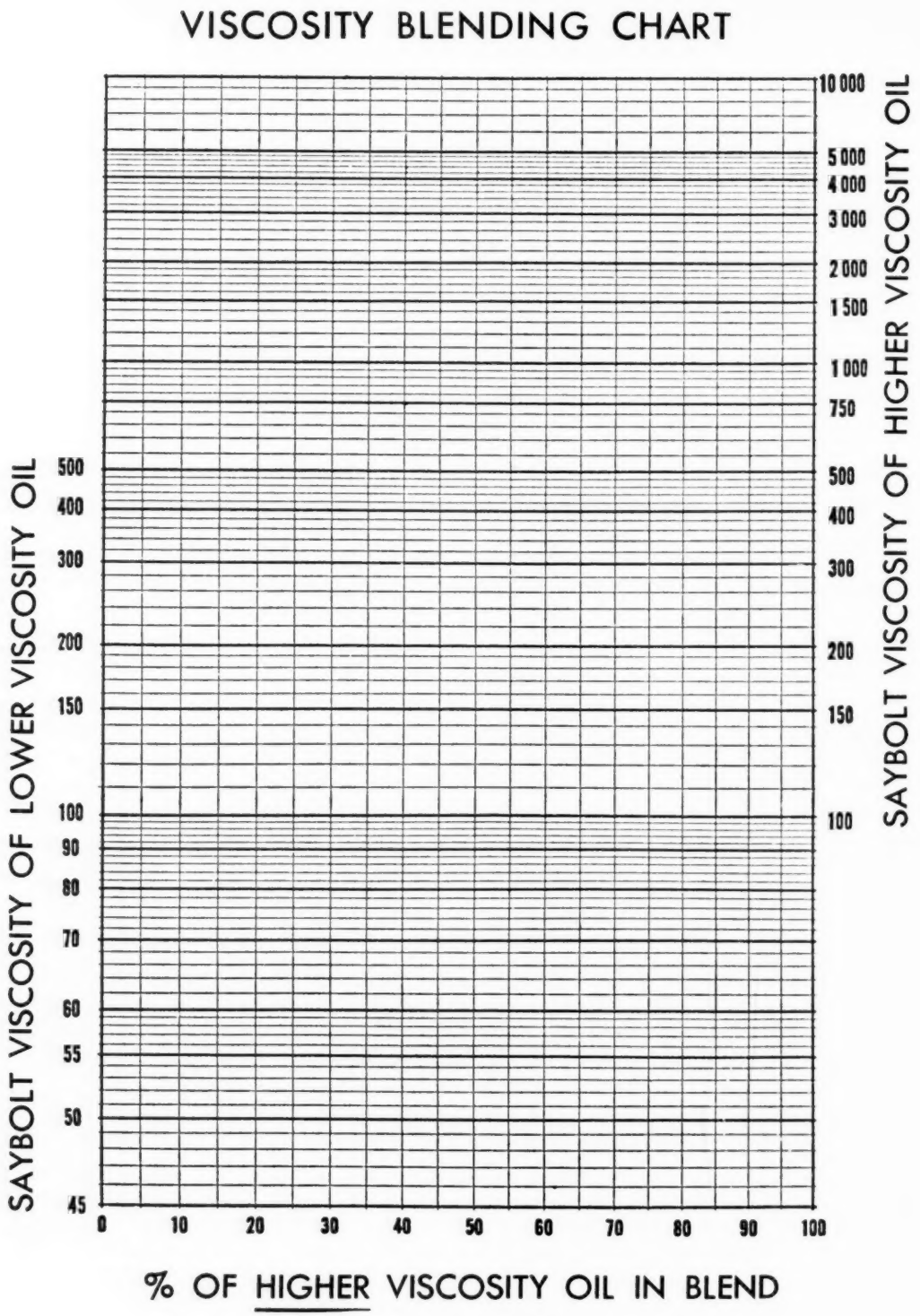


Figure 26 — Viscosity Blending Chart.

a short cylindrical "sinker" is used. The tube, of course, is made of steel to withstand high pressures and the fall of the sinker when the tube is inverted is indicated by means of electrical contacts. Publication of the work of this committee at an early date will be awaited with interest.

PART V – VISCOSITY INDEX

It is frequently desirable to indicate in some simple terminology the relative rate of change of viscosity of a given oil with temperature. A system called Viscosity Index was introduced by E. W. Dean and G. H. B. Davis[29] for this purpose, and it has served so well that it is now in wide use.

The original viscosity index system was set up by an arbitrary selection of two series of oils derived from opposite extreme types of crude oil: the "H" series having the less change in viscosity with temperature, and the "L" series the greater change. Seven blends were made up in each series, with viscosities varying from about 200 to 1200 seconds Saybolt at 100°F. Each oil in the "H" series was arbitrarily assigned a V.I. value of 100, whereas each oil in the "L" series was assigned a V.I. value of 0. In practice a reference oil is selected from each series, with the same viscosity at 210 as an oil to be evaluated. The numerical difference in viscosities of these two oils at 100°F. will always, by definition, represent 100 V.I. divisions. Thus the V.I. of an oil may be computed by equation 19 below.

Such calculations are generally simplified by means of tables, such as Table II, p. 72.

In use, the table is entered at the 210° viscosity of an oil to be evaluated, and the 100°F. viscosities of the L series, as well as the difference in the 100°F. viscosities of the L and H series (oils having the same 210°F. viscosity as the oil being evaluated) are both taken for use in equation 19.

Thus: the oil designated "PR" in Lane and Dean's data had a viscosity of 80 at 210°F. and 800 at 100°F. The V.I. is therefore:

$$\frac{1627 - 800}{836} \times 100 = 99$$

where 1627 is the viscosity at 100 degrees Fahr. of reference oil of 0 V.I. having the same 210 degrees Fahr. viscosity as the oil being evaluated. 836 is the difference between the 100 degrees Fahr. viscosities of the 0 and 100 V.I. oils.

0 to 100 Not the Confining Limits

While it was probably assumed originally that the V.I. of all oils would fall between the L and H series, some oils are now in use which are less sensitive to temperature than the 100 V.I. series, and others are more sensitive than the zero V.I. series.

Thus Viscosity Indexes over 100 are experienced as well as less than 0; in other words, negative values. For example, the sample designated "T-V-275" from the same source,[15] had a viscosity of 49 at 210 and 460 at 100°. The V.I. is consequently

$$\frac{386.2 - 460}{147.2} \times 100 = -50.2$$

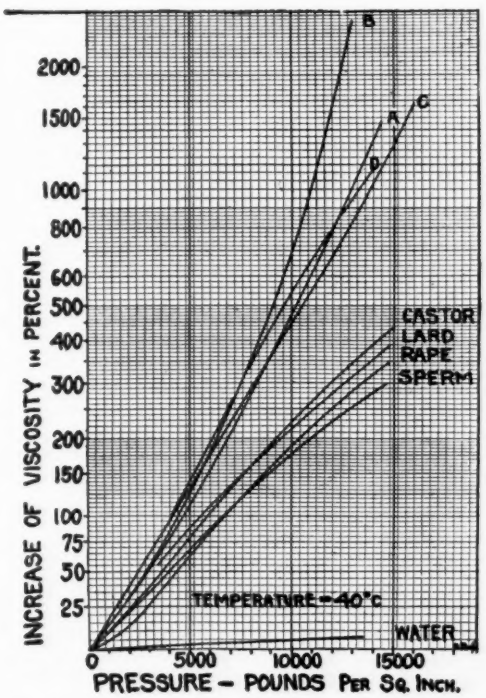


Figure 27 – Showing the effect of pressure on viscosity. The group of fatty oils is much less affected than the mineral oils represented by lines A to D. Notice that water is affected but little.

$$\frac{\text{V.I.}}{100} = \frac{\text{difference between 100°F. viscosities of L Series and unknown oil}}{\text{difference between 100°F. viscosities of L and H Series oils.}} \quad \ldots (19)$$

[29] Chem. & Met. Eng. 36 #10, p. 618 (1929).

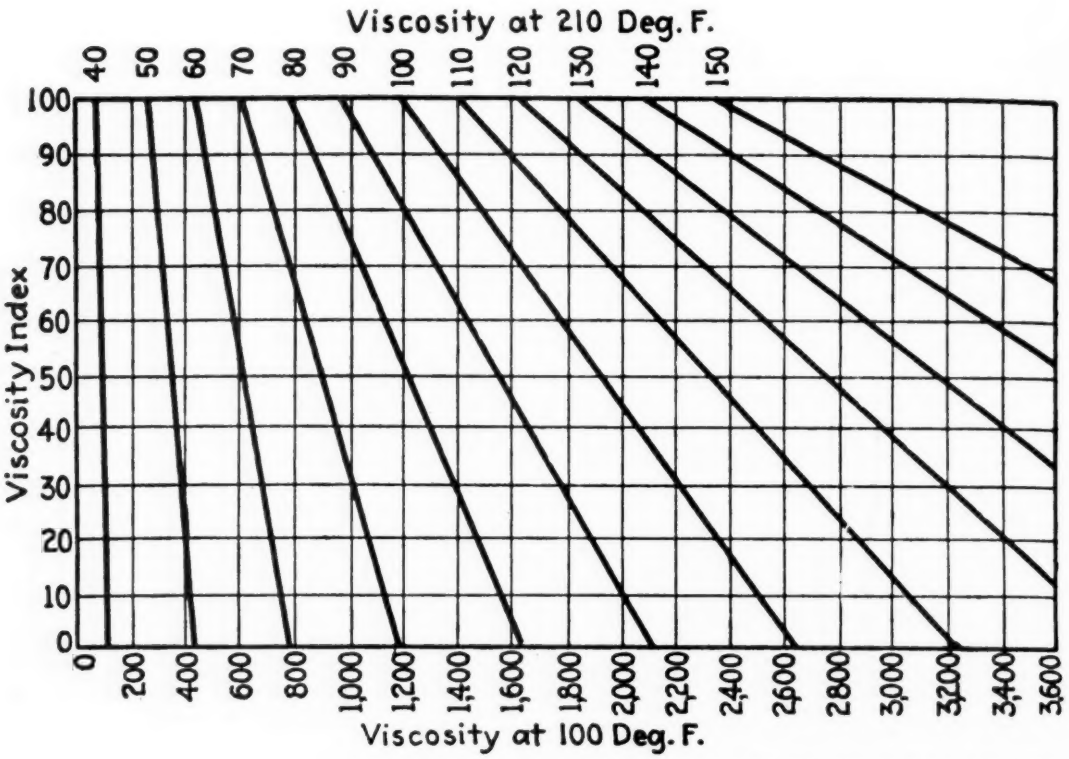
Relation to Kinematic Scale

With the trend in the petroleum industry to measure all viscosities in Kinematic units, tables are now used which indicate V.I. of an oil directly, and without calculation, from the viscosities in centistokes at 100° and 210°F. A sample page from one of these tables is shown in Table III. This page would be used to evaluate an oil having a viscosity in the range from 5.65 — 5.69 cs at 210°F. and V.I. in the range from 60 to 120. To evaluate an oil of 5.66 cs at 210°F. and 40 cs at 100°F., run down the column headed 5.66 to 40.00, where it will be seen that the V.I. (in the column to the left) is 84.

For those who prefer graphical solutions a chart such as Figure 28 may be used. This was taken from the original article by Dean and Davis.[29] An example for its use may be indicated by assuming an oil with a viscosity of 110 sec. at 210°F. and 2500 sec. at 100°F. Enter the chart along the diagonal line marked 110 at the top, and follow down the diagonal line until it intersects the light vertical line rising from 2500 at the bottom. Follow this intersection horizontally to the scale at the left, where it will be found to have a Viscosity Index of 40.

Such a system as this for relating the viscosity sensitivity of an oil to temperature changes, between two extreme types of arbitrarily selected crudes, might appear to indicate the source of the crude oil from which it was derived. This, however, is not the case since oil refining today may change the V.I. of an oil to a far different value than would normally be expected from unrefined oils from a given crude.

V.I. has only one significance; the rate of change of viscosity with temperature. It does not define nor indicate any other characteristic, nor does it measure the quality of the lubricating oil. In fact, in some applications, such as turbine lubrication, it may be preferable to use low V.I. oils so as to take advantage of relatively high viscosities on starting and lower viscosities as the oil warms up to running temperatures.



Courtesy: Chem. & Met. Eng. Vol. 36 #10 p. 618 (1929).

Figure 28 — Viscosity Index Chart.

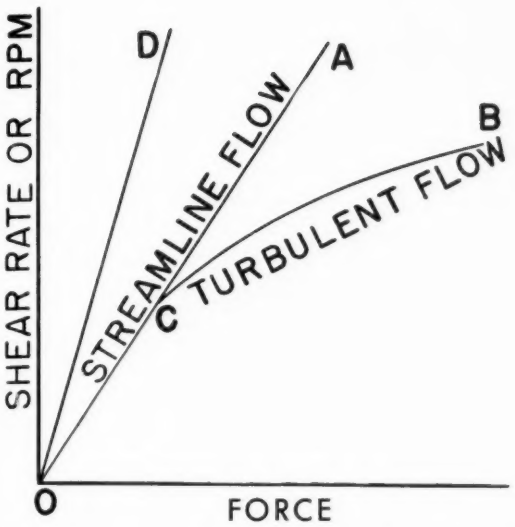


Figure 29 — Viscous flow characteristics; force-shear rate lines pass through origin.

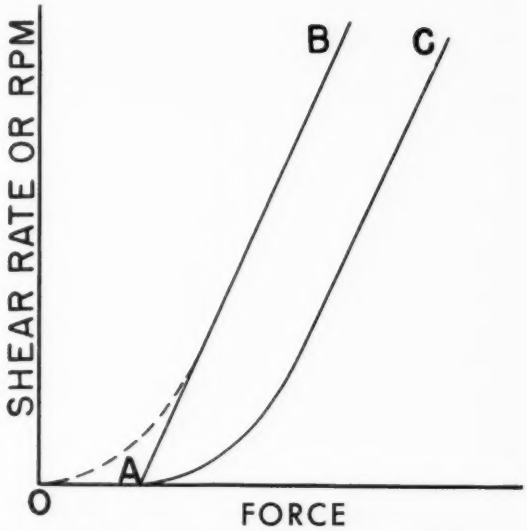


Figure 30 — Plastic flow characteristics; normal flow or shear rate is not established until some critical yield point is exceeded.

PART VI — PLASTICITY

The material presented on streamline flow of fluids, may be summarized by referring to Poiseuill's Law as expressed in the definition of the Poise (p. 50) as a fundamental unit in measurement of viscosity. Notice that in this definition, fluid flow as measured by velocity or volume, varies directly with the applied force, no matter how small this may be. This is illustrated by the straight line OA in Figure 29, which by the definition passes through the origin. Similar lines for different viscosities will have different slopes, such as OD for a lower viscosity, which of course has a greater flow when subjected to a given force. Conversely, no matter how viscous the fluid may be, application of a shear producing force will cause flow. No matter how slow this flow may be, the line representing the force-flow relations will *pass through the origin.* This is essential in the understanding of the present use of the word *fluid* (whether liquid or gas).

In Part III it was shown that as the flow rate of a fluid is steadily increased, a critical region will be reached eventually, where the streamline flow represented by a straight line such as OA or OD in Figure 29, will merge into a region of turbulent flow which will be represented by a curved line, such as CB which represents a much slower increase of flow rate for a given increase of the applied force.

With these characteristic features of fluid flow clearly outlined, the distinguishing differences of plastic flow may be appreciated. Plastic materials are characterized by their ability to withstand a certain limiting sheer force indefinitely without flow, but after this limit is exceeded, flow results which increases with the magnitude of the force. This is illustrated in Figure 30. When a force equivalent to OA is exceeded, flow will result which may follow a line such as AB or a curve such as AC, depending on the material. The rate of flow, or the slope of the line, is controlled by a characteristic similar to fluidity in fluids (the inverse of viscosity), but is designated as Mobility. Thus the flow characteristics of a plastic material require knowledge of both the yield point, and mobility in order to be identified as definitely as a fluid is by its viscosity.

In practice, plasticity may be measured by torsion viscometers from readings made at two or more speeds. The instrument illustrated in Figure 5 (see May issue) has several speeds provided for this purpose in the gear trains. Torsion instruments which use a falling weight to rotate a cup or rotor, such as shown in Figures 2 and 3, may reveal plastic data, by tests run with different weights. Efflux viscometers may be used also, if the pressure causing flow is variable, as when caused by air pressure instead of gravity.

There are many industries where the measurement and control of plasticity are required, typical among them being the manufacturers of paint. The

petroleum industry's use of such measurements consists primarily in the control of the consistency of greases. To a lesser extent it is also interested in control of the consistency of "mud" used in deep oil well drilling operations.

Lack of space prevents further consideration of plasticity, but the subject has been included here to show that most solids (plastic materials) exhibit a characteristic similar to the viscosity of fluids, when subjected to shear stresses beyond their yield points. Processes in which metals are formed at any temperature below their melting points are in this category, and include forging, wire drawing, extrusion, etc.

TABLE II

Abridged V.I. Table for Saybolt Viscosities
(ASTM D 567-41)

H = Viscosity at 100 F. of an oil of 100 viscosity index.
L = Viscosity at 100 F. of an oil of 0 viscosity index.

Saybolt Universal Viscosity at 210 F., sec.	H	L	$\frac{D}{(L-H)}$	Saybolt Universal Viscosity at 210 F., sec.	H	L	$\frac{D}{(L-H)}$
40.0	107.1	137.9	30.8	72.5	651	1290	639
40.5	113.1	147.3	34.2	73.0	660	1311	651
41.0	119.3	157.9	38.6	73.5	669	1333	664
41.5	125.9	169.4	43.5	74.0	678	1355	677
42.0	132.7	181.7	49.0	74.5	688	1377	689
42.5	139.7	194.7	55.0	75.0	697	1399	702
43.0	146.9	208.4	61.5	75.5	707	1422	715
43.5	154.2	222.4	68.2	76.0	716	1444	728
44.0	161.5	236.5	75.0	76.5	725	1468	743
44.5	168.9	250.9	82.0	77.0	734	1489	755
45.0	176.3	265.1	88.8	77.5	744	1512	768
45.5	183.8	279.4	95.6	78.0	753	1534	781
46.0	191.3	293.9	102.6	78.5	763	1557	794
46.5	198.7	308.4	109.5	79.0	772	1580	808
47.0	206.3	322.4	116.2	79.5	782	1604	822
47.5	214.0	337.0	123.0	80.0	791	1627	836
48.0	222.0	352.3	130.3	80.5	801	1651	850
48.5	230.3	368.5	138.2	81.0	810	1674	864
49.0	239.0	386.2	147.2	81.5	820	1698	878
49.5	247.2	404.2	157.0	82.0	829	1721	892
50.0	255.1	422.0	166.9	82.5	839	1745	906
50.5	263.4	439.2	175.8	83.0	849	1769	920
51.0	271.7	456.1	184.4	83.5	859	1793	934
51.5	280.0	473.1	193.1	84.0	868	1817	949
52.0	288.4	490.5	202.1	84.5	878	1841	963
52.5	296.8	507.7	210.9	85.0	888	1865	977
53.0	305.3	525.2	219.9	85.5	898	1890	992
53.5	313.8	543.0	229.2	86.0	907	1914	1007
54.0	322.2	560.5	238.3	86.5	917	1939	1022
54.5	330.7	578.1	247.4	87.0	927	1964	1037
55.0	339.2	596.0	256.8	87.5	937	1989	1052
55.5	347.8	614.1	266.3	88.0	947	2014	1067
56.0	356.4	632.5	275.9	88.5	957	2039	1082
56.5	364.9	650.2	285.3	89.0	966	2064	1098
57.0	373.5	668.6	295.1	89.5	976	2090	1114
57.5	382.2	687.0	304.8	90.0	986	2115	1129
58.0	390.8	705.5	314.7	90.5	996	2141	1145
58.5	399.4	723.9	324.5	91.0	1006	2166	1160
59.0	408.2	742.8	334.6	91.5	1016	2192	1176
59.5	416.9	761.7	344.8	92.0	1026	2217	1191
60.0	425.6	780.6	355.0	92.5	1036	2244	1208
60.5	434.3	799.7	365.4	93.0	1046	2270	1224
61.0	443.1	818.9	375.8	93.5	1056	2296	1240
61.5	451.9	838.1	386.2	94.0	1066	2322	1256
62.0	460.6	857.4	396.8	94.5	1077	2349	1272
62.5	469.5	876.9	407.4	95.0	1087	2375	1288
63.0	478.4	896.5	418.1	95.5	1097	2402	1305
63.5	487.2	916.2	429.0	96.0	1107	2428	1321
64.0	496.1	936.2	440.1	96.5	1118	2455	1337
64.5	505.0	955.9	450.9	97.0	1128	2481	1353
65.0	514.0	976.1	462.1	97.5	1138	2509	1371
65.5	522.9	996.2	473.3	98.0	1148	2536	1388
66.0	531.8	1016.3	484.5	98.5	1158	2564	1406
66.5	540.8	1036.7	495.9	99.0	1168	2591	1423
67.0	549.8	1057.1	507.3	99.5	1179	2619	1440
67.5	558.9	1077.7	518.8	100.0	1189	2646	1457
68.0	567.8	1098.3	530.5	101.0	1210	2701	1491
68.5	577.0	1119.2	542.2	102.0	1231	2757	1526
69.0	586.1	1140.1	554.0	103.0	1252	2814	1562
69.5	595.2	1161.1	565.9	104.0	1273	2870	1597
70.0	604	1182	578	105.0	1294	2928	1634
70.5	614	1204	590	106.0	1315	2985	1670
71.0	623	1225	602	107.0	1337	3043	1706
71.5	632	1247	615	108.0	1358	3102	1744
72.0	641	1268	627	109.0	1379	3161	1782

TABLE III

Sample Page from V.I. Tables for Basic Kinematic Viscosities (compiled by The Texas Company)

	Kinematic viscosity at 210°F.									
	5.65		5.66		5.67		5.68		5.69	
V.I.	KIN. at 100°	KIN. at 150°	KIN. at 100°	KIN. at 150°	KIN. at 100°	KIN. at 150°	KIN. at 100°	KIN. at 150°	KIN. at 100°	KIN. at 150°
60	44.32	14.07	44.47	14.10	44.61	14.13	44.75	14.17	44.90	14.20
61	44.14	14.04	44.28	14.08	44.42	14.11	44.57	14.15	44.71	14.18
62	43.95	14.02	44.10	14.06	44.24	14.09	44.38	14.12	44.52	14.16
63	43.77	14.00	43.91	14.03	44.05	14.07	44.19	14.10	44.33	14.13
64	43.58	13.98	43.72	14.01	43.86	14.04	44.00	14.08	44.14	14.11
65	43.40	13.95	43.54	13.99	43.68	14.02	43.82	14.05	43.95	14.09
66	43.21	13.93	43.35	13.97	43.49	14.00	43.63	14.03	43.77	14.06
67	43.03	13.91	43.17	13.94	43.30	13.98	43.44	14.01	43.58	14.04
68	42.84	13.89	42.98	13.92	43.12	13.95	43.25	13.99	43.39	14.02
69	42.66	13.86	42.79	13.90	42.93	13.93	43.06	13.96	43.20	13.99
70	42.47	13.84	42.61	13.87	42.74	13.91	42.88	13.94	43.01	13.97
71	42.29	13.82	42.42	13.85	42.55	13.88	42.69	13.91	42.82	13.95
72	42.10	13.79	42.24	13.83	42.37	13.86	42.50	13.89	42.63	13.92
73	41.92	13.77	42.05	13.80	42.18	13.83	42.31	13.87	42.44	13.90
74	41.73	13.75	41.86	13.78	41.99	13.81	42.12	13.84	42.25	13.88
75	41.55	13.72	41.68	13.76	41.81	13.79	41.94	13.82	42.07	13.85
76	41.36	13.70	41.49	13.73	41.62	13.76	41.75	13.80	41.88	13.83
77	41.18	13.68	41.30	13.71	41.43	13.74	41.56	13.77	41.69	13.80
78	40.99	13.65	41.12	13.69	41.25	13.72	41.37	13.75	41.50	13.78
79	40.81	13.63	40.93	13.66	41.06	13.69	41.18	13.73	41.31	13.76
80	40.62	13.61	40.75	13.64	40.87	13.67	41.00	13.70	41.12	13.73
81	40.44	13.58	40.56	13.61	40.68	13.65	40.81	13.68	40.93	13.71
82	40.25	13.56	40.37	13.59	40.50	13.62	40.62	13.65	40.74	13.68
83	40.07	13.53	40.19	13.57	40.31	13.60	40.43	13.63	40.55	13.66
84	39.88	13.51	40.00	13.54	40.12	13.57	40.24	13.60	40.37	13.64
85	39.70	13.49	39.82	13.52	39.94	13.55	40.06	13.58	40.18	13.61
86	39.51	13.46	39.63	13.49	39.75	13.52	39.87	13.55	39.99	13.59
87	39.33	13.44	39.44	13.47	39.56	13.50	39.68	13.53	39.80	13.56
88	39.14	13.41	39.26	13.44	39.38	13.47	39.49	13.51	39.61	13.54
89	38.96	13.39	39.07	13.42	39.19	13.45	39.31	13.48	39.42	13.51
90	38.77	13.36	38.89	13.39	39.00	13.42	39.12	13.46	39.23	13.49
91	38.59	13.34	38.70	13.37	38.81	13.40	38.93	13.43	39.04	13.46
92	38.40	13.31	38.51	13.34	38.63	13.37	38.74	13.41	38.85	13.44
93	38.22	13.29	38.33	13.32	38.44	13.35	38.55	13.38	38.67	13.41
94	38.03	13.26	38.14	13.29	38.25	13.32	38.37	13.35	38.48	13.38
95	37.85	13.24	37.96	13.27	38.07	13.30	38.18	13.33	38.29	13.36
96	37.66	13.21	37.77	13.24	37.88	13.27	37.99	13.30	38.10	13.33
97	37.48	13.19	37.58	13.22	37.69	13.25	37.80	13.28	37.91	13.31
98	37.29	13.16	37.40	13.19	37.51	13.22	37.61	13.25	37.72	13.28
99	37.11	13.14	37.21	13.17	37.32	13.20	37.43	13.23	37.53	13.26
100	36.92	13.11	37.03	13.14	37.13	13.17	37.24	13.20	37.34	13.23
101	36.73	13.09	36.84	13.12	36.95	13.15	37.05	13.18	37.16	13.20
102	36.55	13.06	36.65	13.09	36.76	13.12	36.86	13.15	36.97	13.18
103	36.36	13.04	36.47	13.06	36.57	13.09	36.67	13.12	36.78	13.15
104	36.18	13.01	36.28	13.04	36.38	13.07	36.49	13.10	36.59	13.13
105	35.99	12.98	36.10	13.01	36.20	13.04	36.30	13.07	36.40	13.10
106	35.81	12.96	35.91	12.99	36.01	13.02	36.11	13.04	36.21	13.07
107	35.62	12.93	35.72	12.96	35.82	12.99	35.92	13.02	36.02	13.05
108	35.44	12.90	35.54	12.93	35.64	12.96	35.73	12.99	35.83	13.02
109	35.25	12.88	35.35	12.91	35.45	12.94	35.55	12.96	35.64	12.99
110	35.07	12.85	35.17	12.88	35.26	12.91	35.36	12.94	35.46	12.97
111	34.88	12.83	34.98	12.85	35.08	12.88	35.17	12.91	35.27	12.94
112	34.70	12.80	34.79	12.83	34.89	12.85	34.98	12.88	35.08	12.91
113	34.51	12.77	34.61	12.80	34.70	12.83	34.80	12.86	34.89	12.88
114	34.33	12.75	34.42	12.77	34.51	12.80	34.61	12.83	34.70	12.86
115	34.14	12.72	34.24	12.75	34.33	12.77	34.42	12.80	34.51	12.83
116	33.96	12.69	34.05	12.72	34.14	12.75	34.23	12.77	34.32	12.80
117	33.77	12.66	33.86	12.69	33.95	12.72	34.04	12.75	34.13	12.77
118	33.59	12.64	33.68	12.66	33.77	12.69	33.86	12.72	33.94	12.75
119	33.40	12.61	33.49	12.64	33.58	12.66	33.67	12.69	33.76	12.72

RETROSPECT

It has been the intention in gathering together these notes on the broad subject of viscosity, to present material for convenient reference which has been published in LUBRICATION from time to time. Additional material has been added to give a rounded picture of the general subject. While the text has been intended for the casual reader, references and equations have been given in footnotes, so that those technically interested may refer to the original sources of information for further study.

The significance of viscosity in evaluating the performance of lubricants, the ability to sustain loads in bearings, the effect on oil consumption and wear in engines, have also been covered from time to time in past issues of LUBRICATION. Further application of the significance of viscosity at this time is outside the scope of this article.

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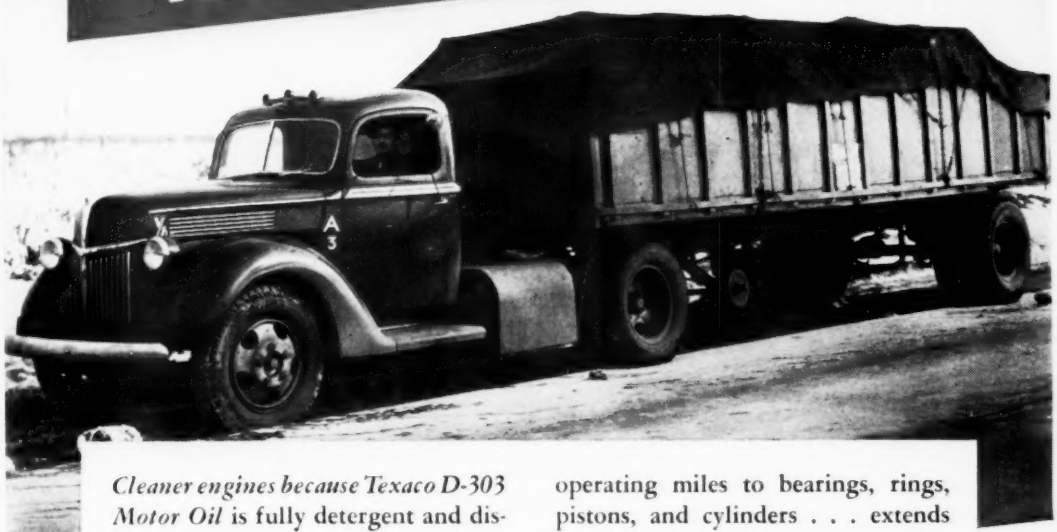

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